

## Preserving low-frequency climate signals in growth records of geoduck clams (*Panopea abrupta*)

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### Abstract

The capacity of geoduck clams (*Panopea abrupta*) to preserve detailed records of climatic change in their shells is limited primarily by longevity. Unlike the multi-centennial growth records commonly available from trees, shells rarely yield more than 160 years of data; consequently low-frequency signals may be lost when band width series are processed.

Here we investigate use of ‘Regional Curve Standardization’ (RCS) to preserve decadal to centennial-scale growth trends in the relatively short segment lengths available from individual clams. Advantages of this method over the more common ‘exponential’ treatment are first explored through simulation experiments using sine waves embedded in geoduck growth curves. Both standardization methods are then used to remove biological trends from growth records of geoduck shells sampled near Protection Island, in the Strait of Juan de Fuca. The resulting chronologies are compared in terms of their spectral properties, their correlations with historical air temperature records and their agreement with historical observations of the marine environment.

Simulation experiments illustrated the potential benefits of using the RCS growth model to standardize shell growth series, but empirical results were inconclusive. The RCS chronology exhibited enhanced spectral power at periods exceeding the length of growth segments, and provided stronger correlation with coastal air-temperature records, especially during the earliest portion of the chronology. Over the full period of comparison, however, the correlation coefficients were essentially identical.

Observational data from the mid to late 1800s appears to support the RCS results. Northward range expansions of several marine fish species coincide with a period of conspicuously high values in the RCS chronology, and suggest that the coastal ocean was unusually warm along western North America from the 1850s through the 1870s.

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## 1. Introduction

Growth increments in geoduck clams are in many respects analogous to tree-rings. Given the right conditions, both are capable of recording past climatic variability in annually resolved layers. Geoduck shell growth varies with temperature (Noakes and Campbell, 1992; Strom, 2003), and methods used to obtain climate signals from trees have successfully been adapted for use with geoducks (Strom, 2003; Strom et al., 2004) yielding growth records of comparable sensitivity and signal strength. In terms of longevity, however, geoducks compare poorly with their terrestrial counterparts. They rarely exceed 160 years in age (Bureau et al., 2002). Consequently, individual growth series, or ‘segment lengths’, are considerably shorter than the multi-centennial growth records available from trees. This poses difficulties when multi-decadal climate signals, which are of particular interest to fisheries managers, need to be preserved in the growth record. There is now broad consensus that climate can dramatically influence recruitment and survival of marine species at multi-decadal to centennial time-scales (Mantua et al., 1997; McGowan et al., 1998; Finney et al., 2002).

Before individual geoduck growth series can be averaged together they must be ‘standardized’ to remove trends unrelated to climate. The rate of shell accretion declines exponentially with age. Growth is rapid the first 10–15 years, but the expansion in shell length essentially stops after age 25 and further shell accretion is then confined to a steady increase in thickness. This biological trend can be effectively modeled and removed using a modified exponential curve (Cook and Kairiukstis, 1990). The drawback with exponential standardization (EXP), however, is that growth trends exceeding the length of individual series may also be fitted and removed in the process.

Regional Curve Standardization (RCS) (Cook et al., 1995) was developed by dendrochronologists to address this problem. Adaptation of the RCS method for sclerochronology is based on the assumption that a single biological growth curve can be constructed for all shells found at a given location to predict the amount of shell accretion that will occur at any given age. The first step in this process is to estimate average shell growth during each consecutive year of growth. For example, the mean growth at age fifteen

can be estimated by averaging all band widths measured at the sample location that were laid down during the fifteenth year of growth. This provides a rough estimate of growth at age fifteen. By extension, a complete biological growth curve can then be modeled by fitting a modified exponential function to the entire set of mean growth values from age one onwards. The resulting ‘regional curve’ provides a smoothed, best estimate of growth at age, and can be used to standardize all band width series at the site regardless of what calendar year the growth occurred. ‘Standardization’ occurs when actual band width measurements are divided by the predicted values. This removes the biological trend and produces a set of dimensionless growth indices exhibiting roughly uniform variance. Because the ‘regional curve’ serves as an empirical baseline of expected growth, any deviation of actual band widths from the predicted RCS values can be investigated as the possible result of forcing by external factors such as temperature.

The theoretical advantage of RCS is that long-term trends in external forcing are less likely to be fitted and removed during the standardization process (Cook et al., 1995). The age-based alignment effectively averages out temporal trends in growth. For example, to estimate mean growth at age fifteen, shells that were fifteen years old in 1994 might be pooled with shells that were the same age in 1884. Extended periods of anomalous growth, either above or below normal, will therefore be averaged out. Because only biological trends are fitted and removed, multi-decadal climate signals are more likely to be preserved in the final chronology.

Figs. 1 and 2 illustrate the differences that can result when the same set of growth measurements are standardized using both the EXP and RCS methods. Fig. 1 shows an actual set of band width measurements (diamonds), plotted along with EXP (black line) and RCS (dotted line) standardization curves. The geoduck shell that these measurements were derived from (Pr7) was 70 years old in 1977 when a climate regime-shift in the North Pacific generated warmer temperatures (Mantua et al., 1997), and growth bands became wider. This influenced the shape of the EXP curve by leveraging predicted values higher. The practical effect of such leverage can be seen in Fig. 2, panel A. Here the standardized EXP growth series (dotted line) is plotted against a

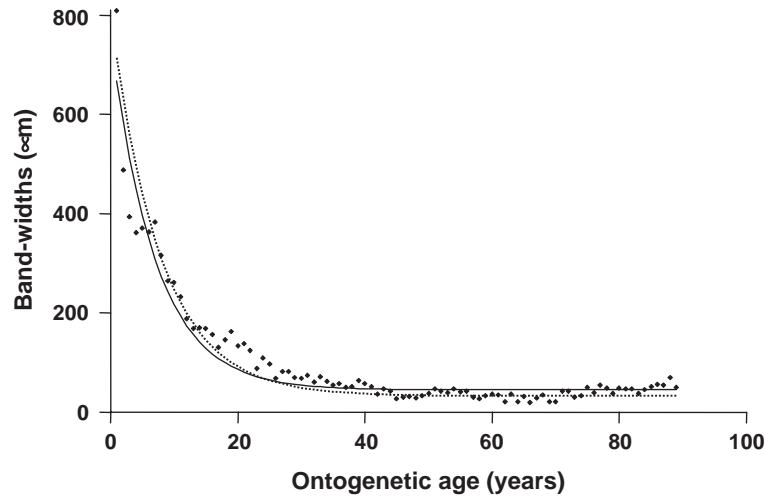


Fig. 1. Band width measurement series from a Protection Island geoduck shell (diamonds), with EXP (black line) and RCS (dotted line) standardization curves superimposed.

local sea-surface temperature (SST) record (black line). The growth series appears to mirror general trends in temperature ( $r=0.41$ ), but amplitudes of

decadal trends are skewed. Values are too high prior to the 1940s and too low after 1977. By contrast, the RCS growth series (Fig. 1, panel B) follows the decadal trends with better fidelity ( $r=0.63$ ).

The most serious potential problem with RCS stems from the underlying assumption that the ‘regional curve’ provides a true estimate of the biological trend for the present, as well as for the distant past (Cook et al., 1995). The ‘true’ shape of the growth curve may, in fact, change over time due to a variety of factors capable of altering ecological or physical site characteristics. Another potential source of error, identified by Briffa et al. (1992), is the tendency of growth series produced by the RCS method to have lower overall common variance than series produced by other methods. Greater series replication would therefore be required to obtain useful results.

The objective of this study was to determine if the potential benefits of RCS warrant its use for processing band width measurements from geoduck shells. Adaptation of the RCS method can best be justified if the resulting chronology provides improved agreement with historical data, and demonstrably preserves multi-decadal variability.

Two separate investigations were conducted. First, the RCS and EXP methods were compared using simulation experiments. An artificial time-series composed of sine waves was embedded in smoothed growth curves derived from shells sampled near Pro-

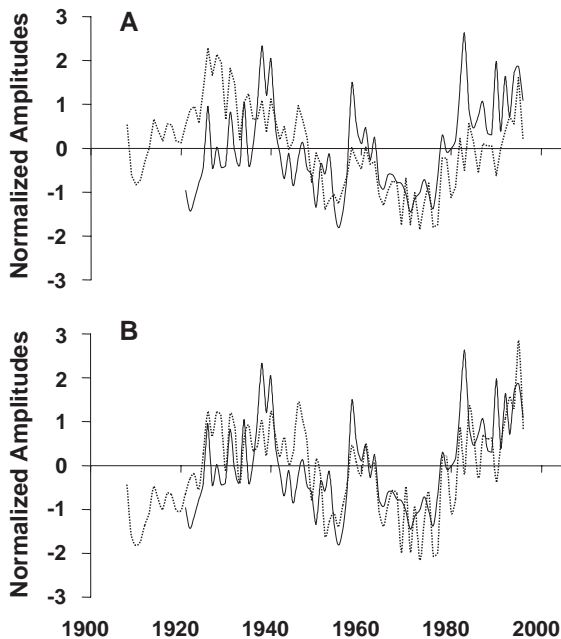


Fig. 2. Standardized growth indices from the measurements depicted in Fig. 1 plotted along with a local SST series (Race Rocks, 1921–1999, black line). The EXP indices (panel A), and RCS indices (panel B) are shown as dotted lines. To facilitate comparison on a common axis all values were normalized by subtracting the series mean and dividing by the standard deviation.

tection Island in the Strait of Juan de Fuca. Biological growth trends were then removed using both standardization methods, and the resulting chronologies compared in terms of their relative skill at preserving the embedded signal. Second, two actual site chronologies were constructed for empirical testing using both the RCS and EXP methods. These were derived from identical sets of shell measurements. The chronologies were compared in terms of their spectral properties, their correlations with historical air temperature records and their agreement with historical observations of the marine environment.

## 2. Materials and methods

### 2.1. Sample site

Shells used in this study were harvested from a subtidal commercial geoduck tract located just west of Protection Island in the Strait of Juan de Fuca (Fig. 3). Depths within the tract range from 9–21 m. Several hundred shells from a naturally occurring population were gathered from a variety of sources over a period of three years beginning in 1999. Most were harvested as part of an ongoing program of biotoxin testing by the Washington Department of Health. Additional shells were acquired from the Washington Department of Fish and Wildlife (WDFW) following stock assessment surveys, and from members of the Jamestown S’Klallam tribe. Because all of the shells were donated, exact locations and depths of individual samples gathered within the tract could not be obtained. It is likely, however, that temperatures and water properties are relatively uniform across the tract due to locally strong currents (Mackas and Harrison, 1997).

The Protection Island tract is located at the eastern end of the Juan de Fuca Strait (Fig. 3), and lies adjacent to the tidal mixing zone at Admiralty Inlet. Intense vertical mixing occurs as water transiting between Puget Sound and the Strait is forced over a relatively shallow (65 m) sill at Admiralty Inlet (Mackas and Harrison, 1997). Tide prediction software (Tides and Currents 2.5) shows that currents 4 km north of Port Townsend (Fig. 1) average ~1.62 m/s at peak daily flow. At Protection Island the mean daily peak flow is ~0.50 m/s. Consequently, water

masses tend to be cool, and relatively resistant to stratification (Strickland, 1983; Newton et al., 1998). For example, during the recent 2000–2001 drought, annual flows in Washington State rivers were reduced by 28–72% (Kimbrough et al., 2002) but Newton et al. (2003) detected no change in stratification at a water sampling station (ADM002) located 9 km NE of Protection Island. By contrast, net declines in stratification averaged 56% at stations in Puget Sound.

Water samples have been collected at the ADM002 station on a monthly basis since 1988 (Newton et al., 1998). This allowed salinity and temperature measurements to be compared over the 10 to 20 m depth range where shells were collected. Values obtained at each depth were averaged for all available years over the March through October period. Winter months were excluded because geoducks tend to be inactive and retract their siphons from November through February (Shaul and Goodwin, 1982). Due to the frequency of missing values in some of the earlier years the period of analysis was restricted to 1991–00. Salinity at 10 m ranged seasonally from 30.26 PSU in March to 31.30 PSU in October. At 20 m, values ranged from 30.31 to 31.53 PSU over the same span. When averaged over all months and years mean salinity ranged from 30.73 PSU (10 m) to 30.89 PSU (20 m). Temperatures differed only marginally between the two depths, with March values actually 0.006 °C warmer at 20 m. Temperatures peaked in August, and the largest spread between depths occurred in October (0.24 °C degrees cooler at 20 m). The Mar–Oct mean over all years and months was 9.87 °C at 10 m versus 9.75 °C at 20 m. Nutrient levels were not measured at ADM002 but tend to be high in the eastern portion of Juan de Fuca Strait throughout the year and at all depths. Surface nitrate typically exceeds 10 µM (Mackas and Harrison, 1997). Chlorophyll varies seasonally, with concentrations estimated to range between 0.5 and 4 mg m<sup>-3</sup> (Mackas and Harrison, 1997). Unfortunately, no useful time-series exist that could serve as a long-term proxy for food abundance.

Geoducks occur over a wide range of depths and habitats in the Puget Sound Basin, from the low intertidal zone to below 100 m, however, preliminary inspection suggested that few sites produced shells

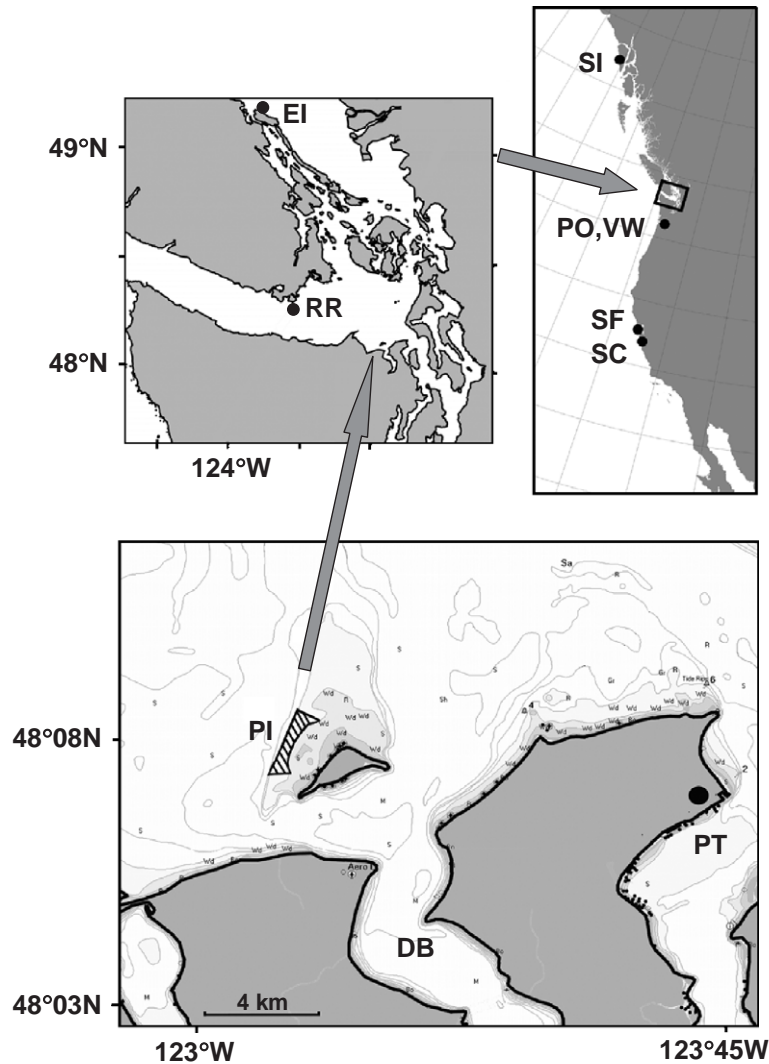


Fig. 3. Map showing the location of the Protection Island tract (PI, bottom panel, area shaded with diagonal lines) and locations where temperature records used in this study originated. Abbreviations in the bottom panel are: DB (Discovery Bay), PT (Port Townsend). Abbreviations in the top left panel: EI (Entrance Island), RR (Race Rocks). Abbreviations in the top right panel: SI (Sitka, Ak), PO (Portland, OR), VW (Vancouver, WA), SF (San Francisco, CA), SC (Santa Cruz, CA).

suitable for climate reconstruction work. The most promising sites, based on sensitivity of growth to temperature, were located in areas of high currents and deep tidal mixing. The least promising were in bays prone to stratification.

The Protection Island tract was selected primarily because of the strong correlation evident between growth and SST (Fig. 2). Such correlation was not evident at Discovery Bay, however, which lies only 3

km SE of Protection Island (Fig. 3). Shells collected in Discovery Bay were considerably larger and thinner. Sporadic monitoring (Newton et al., 1998) shows that Discovery Bay is warmer and more stratified than the eastern portion of Juan de Fuca Strait. The only comparable data available for both ADM002 and Discovery Bay are Mar–Sept measurements from 1991. At 0.5 m the mean temperature at Discovery Bay, averaged over all months, was 12.39 °C, versus



9.64 °C at ADM002. The spread was considerably less at 10 m, with temperatures of 9.95 °C and 9.45 °C respectively. Differences in stratification were most evident during September. The spread in September temperatures between 0.5 and 10 m was 4.19 °C at Discovery Bay versus 0.04 °C at ADM002.

Hoffmann et al. (2000) compared growth rates of geoducks from 11 sites in the Puget Sound region, and found that the slowest growth, as measured by the von Bertalanffy growth parameter  $k$ , occurred at Dallas Bank ( $k=0.1131$ ) which is located in the shallow area directly north of Protection Island (Fig. 3). This site also produced the smallest shells, with a mean shell length of 12.0 cm.

## 2.2. Sample preparation and measurement

Methods for aging geoducks are based on the pioneering work of Shaul and Goodwin (1982). Using mark-recapture studies they established that internal growth increments were annual and that deposition occurred between November and February each year. The annual occurrence of growth banding was later confirmed by Strom (2003) using known-age shells that had been grown from seed in southern Puget Sound. Shaul and Goodwin (1982) found that the most reliable location to count growth increments was in the hinge plate. Our results confirmed this to be true. Cross-sections through the hinge plate provided the clearest, and in most cases, the only, usable view of growth increments.

Shells used in this study were selected for processing based on their weight to length ratio. Thick, heavy shells tend to be older (Bureau et al., 2002), and we were primarily interested in the oldest available shells providing that annuli were distinct and easily readable. Thin-sections were cut from the hinge portion of the shell, mounted on microscope slides and ground thin enough that growth bands were easily visible when viewed using a transmitted light microscope. To enhance visibility of the bands, sections were etched in 1% HCl for approximately 60 s. At least three sections were cut from each shell hinge to assure replication in aging. Digital images were then captured along a straight transect from the origin of growth out to the furthest edge. Transects were selected to avoid areas where bands were indistinct or distorted. Fig. 4 illustrates where sections were

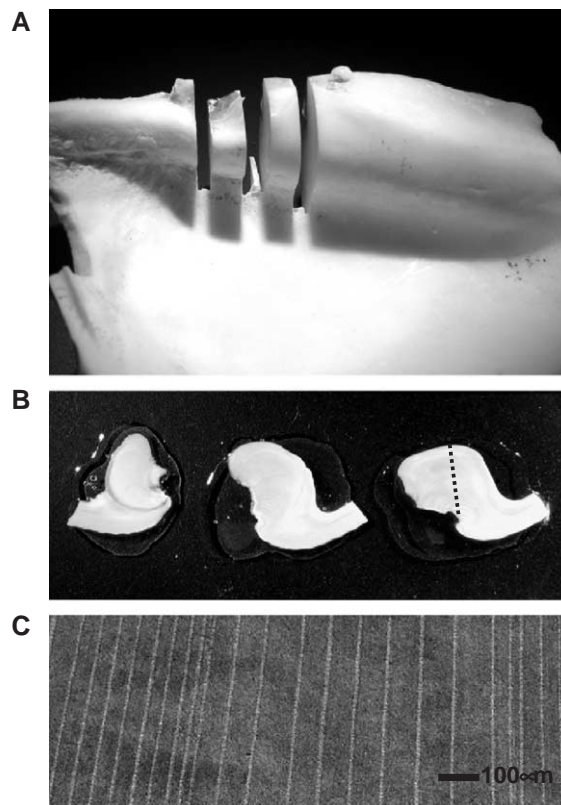


Fig. 4. Panel A shows the location in the shell hinge where thin-sections were extracted. Panel B shows thin-sections mounted on a slide with the location of a typical measurement transect depicted in the section on the right. Panel C shows an image of growth bands taken with a scanning electron microscope.

extracted from the hinge plate (A), how transects might be oriented on a mounted section (B), and shows a scanning electron micrograph of growth bands (C).

Dates were assigned to growth bands by counting back from the year of harvest and were validated by crossdating with replicate sections and sections from other shells. Crossdating (Cook and Kairiukstis, 1990) assures accuracy in dating by matching distinct patterns of narrow or wide bands between growth series. Shells were rejected if results were inconclusive, or if fewer than 40 years were available in a given shell for crossdating. Band widths were measured to the nearest 1 μm using imaging software tools. The final site chronologies spanned from 1844 to 1999, and included a total of 73 sections cut from 25 shells.

### 2.3. Simulation experiments

A set of three replicate simulation experiments were conducted to determine how the RCS and EXP methods compared when confronted with a realistic set of geoduck growth series containing an embedded multi-decadal signal. The ‘signal’ was constructed by adding together two sine curves with periods of 18.6 and 75 years. The composite curve was adjusted to have a mean of one and amplitude ranging from 0.5 to 1.5. This approximated the observed variability of growth indices at Protection Island. The signal was then embedded in 30 simulated growth series, with segment lengths ranging from 75 to 125 years. This matched the distribution of segment lengths among actual samples. The signal was anchored to a starting year of 1850 and was 150 years in length.

The ‘simulated’ growth series were simply randomly assigned exponential curves originally fitted to actual growth measurements of geoducks at least 75 years old. The exponential functions were meant to represent the pure biological growth trend that needed to be removed. To simulate the observed distribution of growth segments in time each artificial series was assigned a random termination date. The first set of 20 segments, 75 years and 100 years long, were randomly terminated between 1975 and 2000. Five segments, 100 years long, ended their age sequence between 1950 and 2000. The remaining five 125-year segments were terminated between 1985 and 2000.

The signal needed to be scaled to each growth series prior to being embedded. This was done by multiplying the signal value for each calendar year by the corresponding value in the growth series. The product was then added back to the growth series producing a final set of simulated geoduck growth measurements consisting solely of an exponential function representing the ‘biological’ trend, and an embedded time-series representing a multi-decadal climate signal.

The objective of the experiment was to compare the relative effectiveness of the RCS and EXP methods at recovering the embedded signal from the same set of simulated measurements. Three replicate trials were conducted. For each trial a new random set of exponential functions served as growth curves, and age 1 of each series was randomly assigned to a new year. To produce the EXP chronologies each set of

simulated measurements were fitted with a modified exponential curve. Standardized growth indices were computed by dividing the simulated measurement in year  $t$  by the predicted growth in year  $t$ . The final chronology was computed by averaging index values for each year. The RCS chronology was computed as described previously. Simulated measurements were aligned by age to construct the RCS curve. Growth indices were then computed by dividing the growth at age in the simulated series by the RCS predicted growth. Finally the standardized series were aligned by calendar year and the chronology was calculated as the arithmetic mean of all standardized indices.

### 2.4. Empirical tests

To compare the RCS and EXP methods using real data two site chronologies were assembled differing only in the method of standardization. The chronologies were developed using the methods described above, but were derived from actual growth measurements from Protection Island. Also, indices were averaged together using a biweight robust mean (Mosteller and Tukey, 1977) rather than the arithmetic mean. The biweight mean is routinely used in dendrochronology to reduce the potential influence of outliers.

To test which standardization method provided the best fit to instrumental data, two sets of coastal temperature data were assembled. The aim was to find a subset of coastal SST data that best correlated with geoduck growth, and then find a second subset of coastal air temperature (AT) data to serve as a proxy for the SST data. Two observations motivated this approach: first, strong correlations exist between AT and SST data in the Puget Sound region (Newton, 1995), and second, SST records extend only about 80 years while AT records extend considerably further. This allowed us to compare the standardization methods using instrumental AT data back to 1850.

Coastal SST data were obtained from Fisheries and Oceans Canada at [http://www-sci.pac.dfo-mpo.gc.ca/osap/data/default\\_e.htm](http://www-sci.pac.dfo-mpo.gc.ca/osap/data/default_e.htm). The Canadian records are the longest SST series available north of California. Additional series exist for Neah Bay, located at the entrance to Juan de Fuca Strait, and for Port Townsend, but these records only extend to 1955 and 1994 respectively. The closest continuous records are from Race Rocks (1921–present), located 46 km NW of

Protection Island, and Entrance Island (1937–present) located 135 km NW (Fig 3). To find the subset of SST data that correlated best with geoduck growth we used the EXP chronology as the benchmark growth series for comparison.

To find an instrumental temperature series that could serve as a proxy for SST we calculated the arithmetic mean of all available AT series from SE Alaska to northern California, provided that they extended at least to the 1870s and either showed a strong marine influence, or were located directly on the coast. AT data were obtained from the Goddard Institute for Space Studies at <http://www.giss.nasa.gov/data/update/csci/>.

Because geoduck shell growth occurs primarily from March through October, all temperature series were calculated for the Mar–Oct period. To allow growth chronologies and temperature records to be compared and plotted using the same units all series were converted to normalized amplitudes by subtracting the series mean and dividing by the standard deviation.

### 3. Results and discussion

#### 3.1. Simulation results

Both the RCS and EXP methods succeeded in recovering the 18.6-year portion of the embedded

signal, however, only the RCS method exhibited skill at preserving the 75-year portion (Fig. 5). This result was in accordance with theory and illustrates the motivation for choosing the RCS method when relatively short time series, such as those available from bivalve shells need to be standardized. The lowest frequency signal that can theoretically be extracted from a time series is equal to  $1/n$  cycles per year (cpy), where  $n$  is the length of the time-series. Cook et al. (1995) estimated that a more realistic limit was  $3/n$  cpy. For the simulation experiment the longest segment length was 125 years ( $n=5$ ), effectively setting the practical limit at 41.6 years. The inability of the EXP method to preserve the 75-year signal was therefore expected. When signals longer than  $3/n$  cpy are of interest the RCS method would be a better choice; this would only be true, however, if it could reasonably be assumed that the relationship between climate and rates of shell accretion at the site in question has remained constant over time.

It is also worth noting that low sample size in the earliest portion of the RCS chronology ( $n \leq 6$ , 1859–1871) did not prevent recovery of the 75-year signal prior to 1871. Provided that the RCS curve is calculated from a sufficiently large pool of shell measurements, even a single shell section may provide an accurate record of multi-decadal trends. This was also illustrated by the standardized measurement series in Fig. 2B, which was derived from a single shell section.

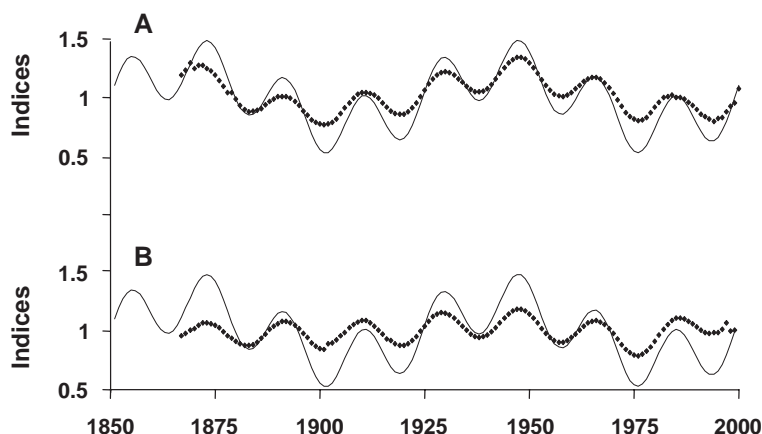


Fig. 5. Panel A shows the mean of three replicate trials (diamonds) using the RCS method to extract an embedded multi-decadal 'signal' from a set of simulated geoduck growth measurements. Panel B shows the mean of three identical trials using the EXP method. The 'signal' (black line) was composed of 18.6-year and 75-year sine waves.



### 3.2. Empirical results

The strongest correlation between the EXP benchmark growth series and SST was obtained when the growth record was compared with a composite of Race Rocks and Entrance Island data averaged over the common period 1937–1999 ( $r=0.73$ ,  $p<0.01$ ). The subset of AT records (1850–1999) that correlated strongest with this composite SST series included records from the following sites (Fig. 3); Sitka, Alaska; Port Townsend, Washington; Vancouver, Washington; Portland, Oregon; San Francisco, California, and Santa Cruz, California. The correlation between the coastal AT series (cAT) and the composite SST series over the common period (1937–1999,  $r=0.81$ ,  $p<0.01$ ) indicated that cAT was a reasonable proxy for Pacific Northwest SST and could be used to test which of the two growth chronologies provided the best fit with instrumental temperature records (Fig. 6).

There was essentially no difference between the RCS and EXP chronologies in terms of their correlation with cAT over the full period of record. For both series the correlation was  $r=0.49$ ,  $p<0.01$  (Fig. 7). During the earlier portion, however, from 1850 to 1936, the correlation with the RCS chronology improved considerably ( $r=0.54$ ,  $p<0.01$ ), while the correlation with the EXP chronology weakened ( $r=0.47$ ,  $p<0.01$ ). The RCS chronology also provided slightly better fit to cAT over the period from 1937 to 1999,  $r=0.60$  for RCS versus  $r=0.58$  for EXP.

The most prominent divergence between the two chronologies encompasses the period from the late 1850s through the 1870s (Fig. 7). The cAT record

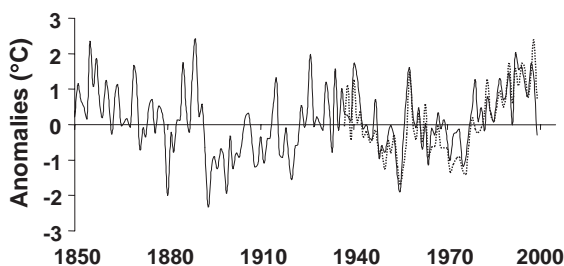


Fig. 6. Comparison between the composite air temperature record (cAT, black line, 1850–1999) and the composite SST record (dotted line, 1937–1999). Correlation between the two series is  $r=0.81$  ( $p<0.01$ ).

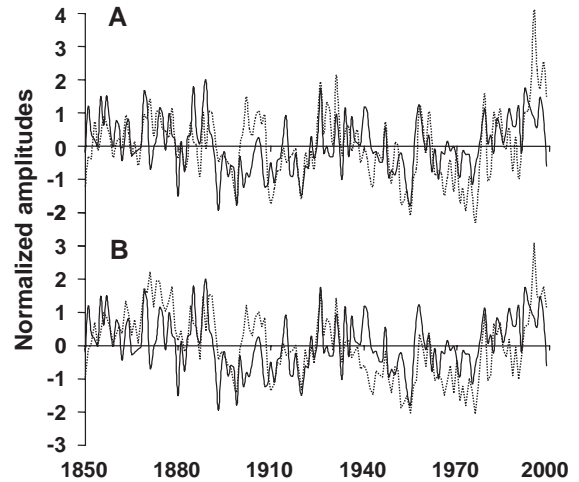


Fig. 7. Comparison between the composite air temperature record cAT, (black lines), and the RCS and EXP chronologies (dotted lines). The EXP chronology is plotted in panel A. The RCS chronology is plotted in panel B. To facilitate comparison on a common axis all values were normalized by subtracting the series mean and dividing by the standard deviation.

indicates that this period was punctuated by occasional spikes of warm temperatures, with peak amplitudes that correspond well with the EXP chronology. By contrast, the RCS chronology suggests a period of unusual and persistent warmth, with temperatures in the 1870s comparable to those in the 1990s.

Despite contrary evidence from the cAT record a considerable body of historical data appears to favor the RCS chronology. Based on extensive historical survey data, Hubbs (1948) documented occurrences of marine species such as giant seahorse (*Hippocampus ingens*), and tropical pipefish (*Dermatostethus punctipinnes*) well north of their normal range. Observations of warm-water fishes in northern waters began in the 1850s and persisted through the 1870s. Hubbs (1948) reasoned that the sensitivity of marine species to small changes in temperature provided sufficient evidence to conclude that conditions were warmer on average in California during this period than over any subsequent period. Citing the same body of evidence, MacCall (1996) speculated that SSTs in the northeast Pacific over this period may have been similar to values recorded after the climate regime-shift of 1976–77 (Mantua et al., 1997). If this interpretation is correct then the strong coherence evident between

coastal SST records ranging from southern California to Juan de Fuca Strait (McGowan et al., 1998) suggests that temperatures would also have been unusually warm at Protection Island. Unfortunately, no instrumental SST data exists for this period to confirm the magnitude of warming, and the cAT record is suspect for the portion prior to the 1880s due to increasing incidence of missing data.

### 3.3. Spectral analysis

We used a combination of methods packaged in the SSA-MTM Toolkit (Ghil et al., 2002) to compare spectral properties of the two chronologies and identify periodic signals. Spectra calculated using the

multi-taper method (Mann and Lees, 1996) indicated that low-frequency power was more pronounced in the RCS chronology (Fig. 8, panel A). At the 99% level the RCS chronology had one significant peak with a period of about 70 years, in addition to a longer trend component. No significant peaks were evident in the EXP chronology (Fig. 8, panel B), and spectral power was reduced at the low-frequency end relative to the RCS chronology.

To identify periodic signals that may have been masked by noise we first reconstructed the RCS chronology using singular-spectrum analysis (SSA) and then subjected the filtered series to multi-taper (MTM) and maximum entropy (MEM) spectral analysis (Ghil et al., 2002). The RCS chronology

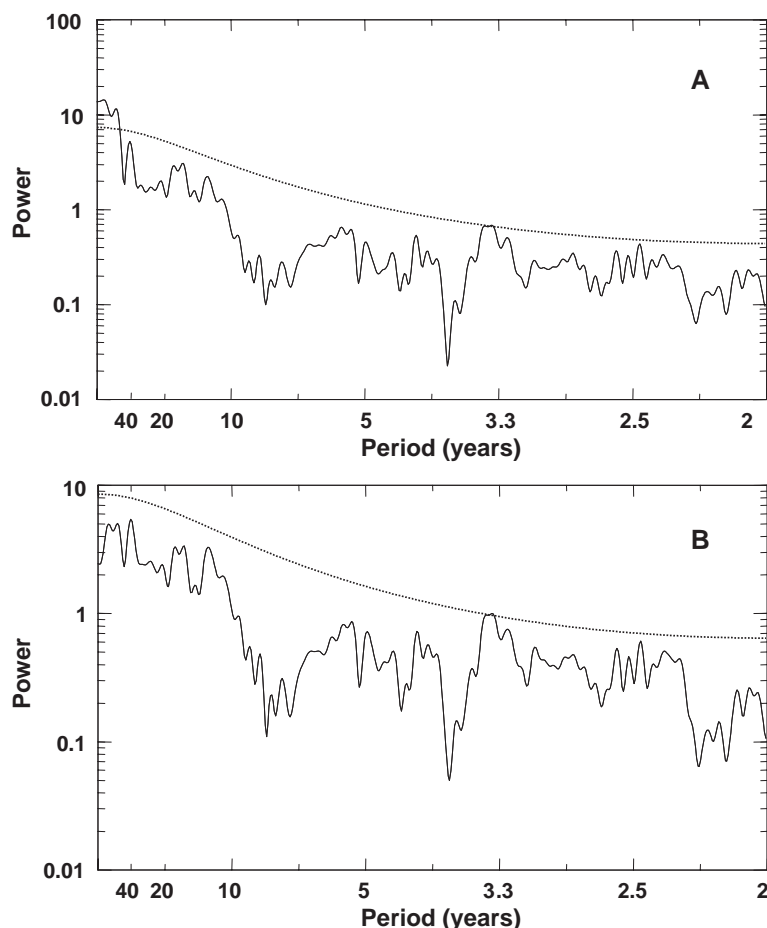


Fig. 8. Comparison between the power spectra of the EXP and RCS chronologies. Spectra were computed using the multi-taper method. Results are plotted as black lines for RCS (panel A) and EXP (panel B). The dotted line indicates the 99% significance level.

was reconstructed using the first 5 components of the SSA eigenvalue spectrum and a window length of  $M=25$ . Results of MEM and MTM analyses are plotted in Fig. 9. Peaks were identified at periods of approximately 70–80 years, 17–19 years, and 11.5 years.

Given the relatively short span of the RCS chronology (149 years) the identification of a peak at 70 years should be treated with caution. The other peaks, however, appear to warrant further investigation. The lunar nodal cycle at 18.6 years and the 11-year solar irradiance cycle have both been linked to variations in ocean temperature through their influence, respectively, on the strength of tidal currents (Parker et al., 1995), winds (Metha and Lau, 1997; Koder, 2003), and solar insolation (White et al., 1997). We found no convincing evidence, however, that either lunar or solar forcing was linearly related to geoduck growth. Linear correlations between the RCS chronology and the best fit 18.6-year lunar signal ( $r=0.04$ ,  $p=0.65$ ), and the monthly mean sunspot numbers ( $r=-0.07$ ,  $p=0.38$ ) were essentially nonexistent. Although it seems likely that both lunar and solar effects contribute to modulating temperature rhythms in the north-east Pacific, defining the exact linkages and mechanisms that may be involved at Protection Island was beyond the scope of this study.

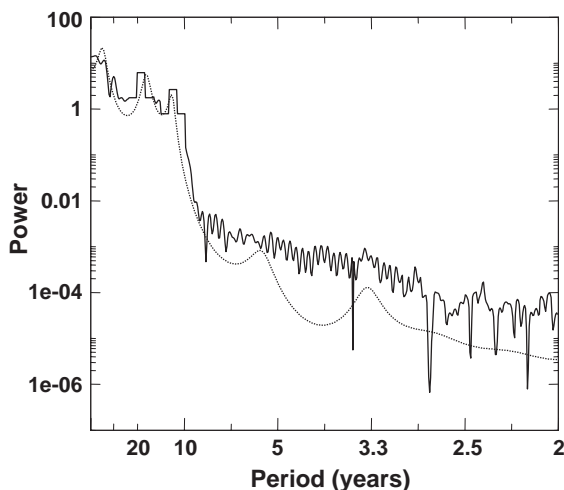


Fig. 9. Spectral analysis of the SSA reconstructed RCS chronology using multi-taper (black line) and maximum entropy (dotted line) methods. Peaks were identified at ~70–80 years, 17–19 years, and 11.5 years.

### 3.4. Summary

The objective of this study was to determine if the potential benefits of RCS warranted adaptation of the method for processing the relatively short band width series available from geoduck shells. Use of RCS can best be justified if the resulting chronology provides improved agreement with historical data, and demonstrably preserves multi-decadal variability. Although results were not conclusive, there was sufficient evidence from the simulated and empirical tests to recommend its use when multi-decadal signals are of interest and site characteristics that may affect shell growth can be assumed to have remained reasonable stable over time.

The simulation experiments clearly illustrated that standardization methods such as EXP, which rely on fitting a relatively flexible curve to sets of growth measurements, are poorly suited to recovering signals that exceed the length of individual segments. RCS may be the best available alternative when multi-decadal signals need to be preserved.

Empirical tests indicated that the RCS method provided marginally better fit to instrumental temperature series. This was particularly true during the earliest portion of the chronology and may be due to better preservation of multi-decadal signals. Spectral analysis indicated that low-frequency power was more pronounced in the RCS chronology.

The divergence evident between the RCS and EXP chronologies during the 1870s provides an empirical test of the two methods that remains unresolved. Fisheries data from this period suggests unusual warming did occur, but available AT data does not. Resolving this question would be valuable not only to improve our understanding of historical climatic variability, but also to learn more about the dynamics of fish populations when confronted with such variability.

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